Laser acceleration of ion beams [1]

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Abstract

We consider methods of charged particle acceleration by means of high-intensity lasers. As an application we discuss a laser booster for heavy ion beams provided, e.g. by the Dubna nuclotron. Simple estimates show that a cascade of crossed laser beams would be necessary to provide additional acceleration to gold ions of the order of GeV/nucleon.

The idea of particle acceleration by means of laser fields was first considered in [1, 2]. Recently, due to the fast development of "table-top" high-intensity lasers with intensities up to 10^{22} W/cm^2 [3], these systems have become interesting for the development of booster systems for the upgrade of existing accelerators which operate just below the threshold for interesting physics. In the case of the Dubna nuclotron an additional acceleration by a few GeV/nucleon would allow studies of the onset of quark matter formation in heavy-ion collisions. Such studies require a fine-tuning in beam energies (energy scan), which be possible with the laser booster provided the required range of acceleration can be reached.

We start by considering the light pressure action on a beam of charged particles. When absorbing a photon the nucleus makes a transition to an excited state and receives an additional velocity in the direction of the photon propagation. After that, the excited nucleus can spontaneously emit a photon and receives some additional momentum. As a result of multiple scattering, the momentum of the nucleus gets incremented along the laser beam. In the oscillator model of nuclei one obtains the following estimate for the light pressure [2]:

$$P = \frac{2\alpha^2}{3\lambda^4}\mathcal{E}^2, \tag{1}$$

where $\mathcal{E} = \sqrt{<\mathbf{E}^2>}$ is the mean electric field strength, $\alpha(\omega)$ is the polarizability of the given nucleus

$$\alpha(\omega) \cong -\frac{e_i^2}{m_i}\sum_n k_n[\omega^2 - \omega_n^2]^{-1}, \tag{2}$$

$\hbar\omega_n$ is the n-th energy level of the nucleus, and k_n is the corresponding oscillator strength taking into account the the specifics of the nucleus.

The application of the light pressure mechanism to the problem of ion acceleration encounters numerous obstacles. First, it is the saturation effect which is associated with the time delay of the vacation of the excited state of nuclei. Second, there is the required condition of resonance between the laser field frequency and nuclear excitation energy.

[1] Talk at the Helmholtz International Summer School "Dense Matter In Heavy Ion Collisions and Astrophysics", JINR, Dubna, August 21 - September 1, 2006.

When the nucleus receives additional energy due to the action of the laser pulse, the condition of resonance brakes because of the Doppler effect and therefore the acceleration force will decrease. The electromagnetic wave frequency in the proper reference frame ω and in the laboratory one ω' are related by by

$$\omega' = \frac{\varepsilon^*}{\hbar}(1+v/c)\gamma, \qquad \gamma = 1/\sqrt{1-v^2/c^2}, \tag{3}$$

where $\varepsilon^* = \hbar\omega$ is the transition energy to an excited state. For the Dubna nuclotron $\gamma \simeq 4$, that corresponds to the ultra-relativistic case and so $\omega' \simeq 2\gamma\varepsilon^*\hbar^{-1}$. If the energy ε^* has the order of some tens of keV (for ^{179}Au we have $\varepsilon^* = 72$ keV), the X-ray laser should have a frequency of the order of 1 MeV. This exceeds considerably the possibilities of modern X-ray lasers [4], for which the typical values of frequencies are less than 10% of the electron mass.

In case of optical lasers, when the frequency is much smaller than the lowest nuclear excitation level, there are other ways of charged particle acceleration by means of the action of gradient forces caused by the interaction between ions and the envelope of the laser electrical field. Let us consider a harmonic field $\mathbf{E}(\mathbf{r},t) = \mathbf{E}(\mathbf{r})\exp(i\omega t)$. The corresponding gradient force is [2, 5, 6]

$$\mathbf{F} = \alpha\nabla\mathcal{E}^2. \tag{4}$$

Under the action of such force, ions move aside to decrease their potential energy and get localized in the knots of the wave. In each point the gradient force has transverse and longitudinal components but the average of the longitudinal component vanishes. Under the action of the gradient force particles are localized in potential wells. As was shown in [7] using special fluctuations with various frequencies it is possible to receive a potential profile varying in time. In particular, it is possible to create conditions for accelerated motion of potential wells with particles localized in them. However, there is a grave disadvantage of this method. That is the fact that the accelerated particle oscillates with the frequency of the external field in the local reference frame. The efficiency of such a mechanism is less than that of a linear accelerator. In real laser beams due to the non-uniform radial distribution of intensity the gradient force can expel particles from the laser field. As shown in [8], this effect depends on the relation of the frequency of the external field to the eigenfrequency of the particle oscillation.

Another way to transfer additional energy to charged particles is to construct special geometrical schemes of laser beams. A scheme to accelerate electrons by means of two crossed laser beams was proposed in the works [9]-[11]. The basic idea is to send the electron or ion through the crossing point of two laser beams at an angle θ with respect to each beam direction [12]. Such a geometry allows to create some longitudinally pulling electric field

$$E_z = -2E_0\, g(\eta)\, \sin\theta\, \cos\eta, \qquad \eta = \omega\,[\,t-(z/c)\cos\theta], \tag{5}$$

where $g(\eta)$ is some envelope function. The ion energy gain, as a result of the interaction with $\eta/2\pi$ cycles of the accelerating field, may be defined by

$$\begin{aligned} W(\eta) &= mc^2\left[\frac{s\cos\theta+\sqrt{s^2+\sin^2\theta}}{\sin^2\eta} - \gamma_0\right], \\ s &= \gamma_0(\beta_0-\cos\theta) + 2qf(\eta)\sin\theta, \end{aligned} \tag{6}$$

where γ_0 is initial value of the Lorentz-factor for $\beta_0 = v_0/c$,

$$f(\eta) \quad = \quad \int_{\eta_0}^{\eta} g(\eta') \cos \eta' d\eta', \tag{7}$$

$q = ZeE_0/(Mc\omega)$ for an ion with electrical charge Ze and a mass M.

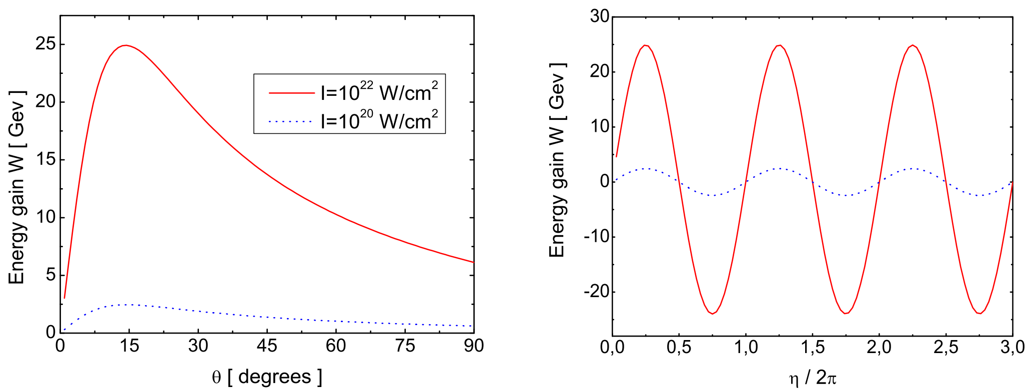
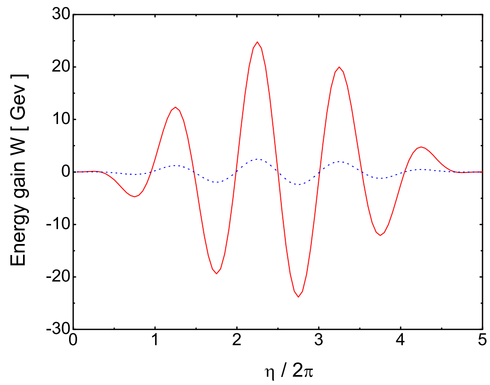


Figure 1: The energy gain of fully ionized gold ions Au^{79+} vs. the crossing half-angle θ for $\eta = \pi/2$ (left) and also vs. the number of field cycles for θ=$\theta_{\max}$=14°(right), γ_0=4, g(η)=1.

The size of the energy increment depends on the crossing angle. An optimal angle $\theta_{\max}$ exists which corresponds to the maximum energy gain for a given set of laser parameters and particle beam initial conditions. Fig.1 shows, that if the ion-field interaction would be terminated in the neighborhood of any one of the points corresponding to $\eta = (2N + 1/2)\pi$, where N is an integer number, the ion would escape with maximum energy gain. The energy gains tend to get canceled by the energy losses for interaction with an even number of field cycles. For the purpose of acceleration, the assumption is that the ion may be ejected from the region of interaction while it still retains part or all of the energy gained. The calculation shows that the optimal half-crossing angle for Au^{79+} is $\theta_{\max} \approx 14°$ for $g(\eta) = 1$ and $\theta_{\max} \approx 20°$ for the $g(\eta) = \sin^2(\eta/10)$ envelope. The maximal energy gain reaches 25 GeV per ion (140 MeV/nucleon) for a laser intensity of the order of 10^{22} W/cm^2. The value of the optimal angle allows the realization of a cascade of laser - ion beam interactions by means of multiple reflection of the laser beams from a sequence of mirrors positioned symmetric to the beam axis.

The initial condition used here are somewhat artificial. We have simply stated that the ion is born at the origin of coordinates at $t = 0$ inside the plane wave which, by definition, has an infinite extension in both space and time. Fig.2 shows that such an ion tends to gain more energy from the field if it starts off at a higher speed. The gain exhibits saturation with increasing injection energy at about $\gamma_0 \approx 20$ for the parameters used. The radiative losses of the accelerated ion can be evaluated by the relativistic version of the Larmor formula [13] and become negligible.

Our preliminary evaluation shows that the most promising method for the laser acceleration of ions is based on the crossed laser beam scheme. The light pressure mechanism in not relevant due to insufficient frequency of the laser field even for modern X-ray



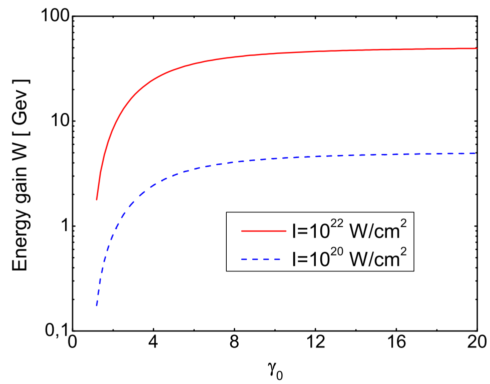


Figure 2: The energy gain of Au^{79+} vs. the number of accelerating field cycles for θ=θ_{max} ≈20° (left) and also vs the initial Lorentz factor γ_0 for $\eta = 9\pi/2$ (right), g(η)= $\sin^2(\eta/10)$. The remaining field parameters used are the same as in Fig.1.

lasers. The action of gradient forces on laser beam is also less effective than the usual linear accelerator scheme. We have disregarded here some effects which are important for the practical realization of the laser booster as, for example, the presence of residual gas in the channel of the ion beam.

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